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CARMA: a new heterogeneous millimeter-wave interferometer

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ABSTRACT

A new Combined Array for Research in Millimeter-wave Astronomy (CARMA) interferometer is being assembled from the existing Owens Valley Radio Observatory (OVRO), the Berkeley-Illinois-Maryland Association (BIMA) millimeter interferometers and the new Sunyaev-Zeldovich Array (SZA) at Cedar Flat, a site at 2,200 m altitude in the Inyo Mountains east of OVRO. The array will consist of 23 antennas of three different diameters, 3.5, 6.1 and 10.4 m, and will support observations in the 1 cm, 3 mm and 1.3 mm bands. The fist-light correlator is a flexible FPGA based system that will process up to 8 GHz of bandwidth on the sky for two subarrays consisting of 8 and 15 elements. The array configurations will offer antenna spacings from 5 m to 1.9 km allowing unprecedented high resolution and wide field imaging at millimeter wavelengths. Radiometers observing the 22 GHz water vapor emission line will be used to measure and correct for the water vapor induced path delay along the line of sight for each telescope and thereby minimize the time lost to "bad seeing". This university based facility will emphasize technology development and student training along with leading edge astronomical research in areas ranging from Sunyaev-Zeldovich effect galaxy cluster surveys to studying protoplanetary disks.

Keywords: Radio Astronomy; Millimeter Interferometry; Antennas; Correlator; Water Vapor Radiometry

1. INTRODUCTION

Millimeter interferometry offers a unique view into the universe that has made significant contributions to many fields of astronomy ranging from planetary atmospheres in our solar system to the large-scale structure of the universe. As with other fields of astronomy, the leading edge instruments continue to increase in size and complexity and the required resources and expertise are larger than can provided by a single institution. The Combined Array for Research in Millimeter-wave Astronomy (CARMA) is a collaboration between five institutions with the goal of improving the sensitivity, image quality and frequency coverage for millimeter interferometry. A previous paper describes the performance parameters for CARMA and many of the interesting projects that it will tackle[1]. This paper will concentrate on the technical aspects of CARMA.

The CARMA array combines six 10.4 m antennas from the Owens Valley Radio Observatory (OVRO) millimeter array[2], nine 6.1 m antennas from the Berkeley-Illinois-Maryland Association (BIMA) array[3] plus eight 3.5 m antennas from the Sunyaev-Zel'dovich Array (SZA) on a new high site at Cedar Flat near OVRO. The OVRO array is operated by the California Institute of Technology while the BIMA array is a collaboration of the Radio Astronomy Laboratory at the University of California (Berkeley), the Laboratory for Astronomical Imaging at the University of Illinois (Urbana-Champaign), and the Laboratory for Millimeter-wave Astronomy at the University of Maryland. The OVRO and BIMA arrays pioneered the field of millimeter interferometry and have played a major role in developing and advancing interferometry in the 3 and 1.3 mm bands. The SZA is being built by the University of Chicago. The partner universities and the National Science Foundation have contributed funding for the project.

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The atmospheric opacity is one of the dominant components that determine the sensitivity of millimeter interferometers. Significant improvements in the scientific capability will result from operating at a higher site, combining more telescopes of three different sizes, implementing an upgraded correlator and migrating to a new distributed control, monitor and data pipeline computing system. The Cedar Flat site is at an elevation of 2,200 m and the annual median 225 GHz zenith opacity is 0.25 nepers, half that of OVRO at an altitude of 1,200 m, allowing observations at 1.3 mm during most of the year. The array configurations and layout are discussed in the next section. The shipping of the antennas to Cedar Flat along with the method for moving the antennas among different configurations is discussed in section 3.

The receivers are another major component affecting the system's sensitivity and it is important to use the best available receivers. CARMA will have state-of-the-art receivers in three bands; 26-36 GHz, 85-115GHz and 205-265 GHz. The decade frequency coverage will be very useful in determining the spectral slope of continuum sources and cover many astronomically interesting molecular lines as well as cover one of the ubiquitous CO lines at almost any redshift. The receivers are discussed in section 4.

The raw output from an interferometer is the spectral cross-correlation of the signal voltages received by pairs of antennas. Typically these visibilities are computed in real-time by either an analog or digital correlator. The number of visibilities scales as the square of the number of antennas and larger arrays require much larger correlators. Increasing the bandwidth and spectral resolution places further demands on the correlator. Section 5 discusses the CARMA correlator. It is based upon the Caltech Ovro Broadband Reprogrammable Array (COBRA) correlator.

The computing and software development is a coordinated effort of 15 programmers working at the embedded processor level up through data pipelines and archiving. The programmers are distributed among the five institutions contributing to CARMA. Section 6 covers some aspects of the computing and programming for CARMA.

The CARMA array will have a total of 23 antennas of 3.5, 6.1 and 10.4 m diameters. The antenna spacings will range from 5 m (3.5 m baselines for near shadowing on the 3.5 m antennas) to 1.9 km. This will recover angular scales from 0.14 arcsec for 1.3 mm observations up to 6 arcmin for 12 mm observations. Heterogeneous array imaging is a new capability for millimeter interferometers and promises to be very useful for producing accurate images of extended objects. Mosaicing plus single dish observations will further extend the imaging capability to much larger fields. An important aspect of CARMA will be the incorporation of water vapor radiometers to correct for the delay variations caused by water vapor and turbulence in the atmosphere. These imaging issues are described in section 7.

The project is well along the way to completion. All of the major hardware changes have been prototyped and are in production. The special use permit from the forest service has been obtained and construction on site has started. The telescope moves will take place starting in the fall of this year with first-light in the spring of 2005. A major goal for CARMA is to continue the student training and instrument development that has played such an important part of previous projects at the participating institutions. To this end innovative development and improvement of the system will continue indefinitely leading to yet another generation of instruments and instrumentalists.

2. SITE DESCRIPTION

An excellent site has been acquired for locating the CARMA array. The site is Cedar Flat in the Inyo Mountains along the east side of the Owens Valley. The water vapor column density at Cedar Flat is low enough to allow routine observations at 230 GHz and is large enough to support baselines up to 2 km. It is also next to a state highway and a 20 minute drive from OVRO and its extensive infrastructure.

The weather in the Inyo Mountains is very favorable for a millimeter array. The Sierra Nevada mountains to the west are very effective at squeezing the moisture out of the general west to east air flow and the annual precipitation is only ~100 mm and the peak snow accumulation is typically less than 200 mm. The winds at Cedar Flat are mild and lower than the winds in the valley where OVRO is located. The OVRO and BIMA telescopes were not designed for the extreme weather conditions such as wind blown snow and freezing ice that are common at the highest mountain sites and it was important to find a site with manageable weather conditions.

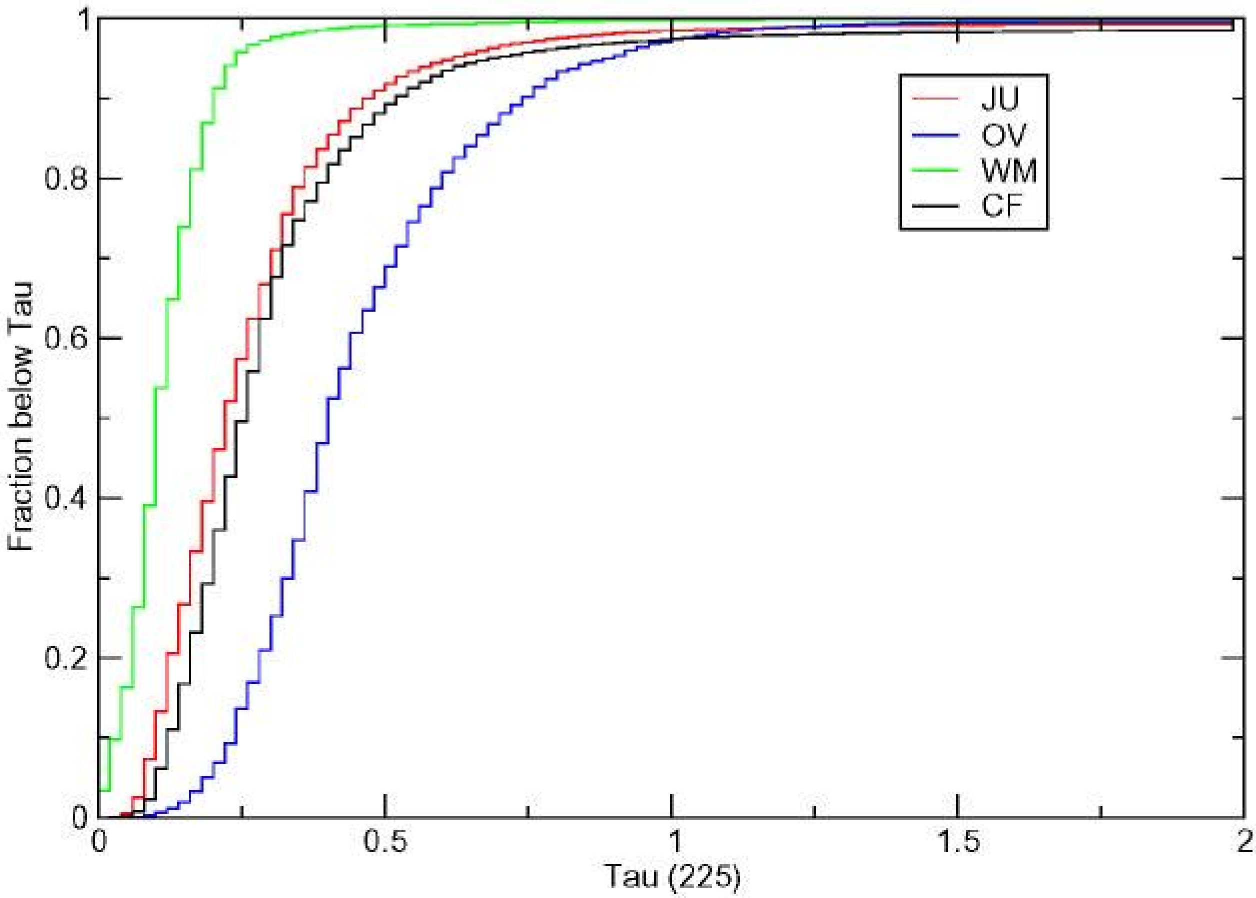


Fig. 1. Cumulative opacity distribution for four sites: OV - the existing Owens Valley Radio Observatory, JU – Juniper Flat, WM – White Mountain Barcroft research station and CF – Cedar Flat.

Approximately two years of continuous weather data were collected at several sites in mountains to the east of OVRO. Figure 1 shows the measured cumulative 225 GHz opacity distribution for these sites. The 225 GHz opacity at Cedar Flat is less than 0.3 nepers for 70% of the time and good 1.3 mm observing condition prevail during most of the year.

Five basic array configurations will utilize 56 pads for the 6.1 m and 10.4 m antennas with baselines ranging from 7 m to 1.9 km. Figure 2 shows a topographic map of Cedar Flat with the location for the antennas in the largest A-array configuration. A simulated view of the antennas in the most compact E-array configuration is shown in Fig. 3. A set of pads for the eight 3.5 m antennas will provide a very compact subarray with pad separations as short as 5 m.

The Forest Service granted CARMA a special use permit for Cedar Flat in February of 2004. The construction of site infrastructure began in May 2004 with the installation of a two-hop microwave relay operating at 5.2 GHz to provide a 45 Mb/s data link to OVRO, with Internet connections to the rest of the world. Improvements to the dirt roads on the site started in June 2004. The infrastructure at Cedar Flat will include a control building, maintenance shop and generator facility. This infrastructure plus the power, fiber cabling and pads for the first 15 stations are scheduled for completion at the end of 2004.

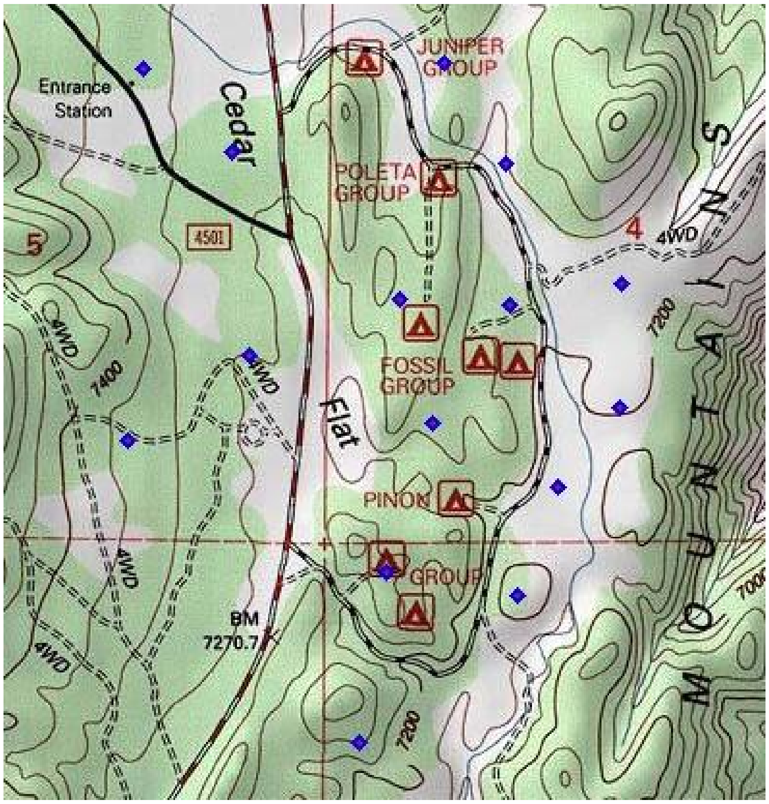


Fig. 2. Largest A-array configuration. The antenna pads are shown as blue/black diamonds. The road running north-south through the site is California state highway 168. The control building and center of the more compact arrays will be located just to the east of the Fossil Group campground. The campgrounds will be relocated ~10km to the west of Cedar Flat. The map shown is ~2km on a side.

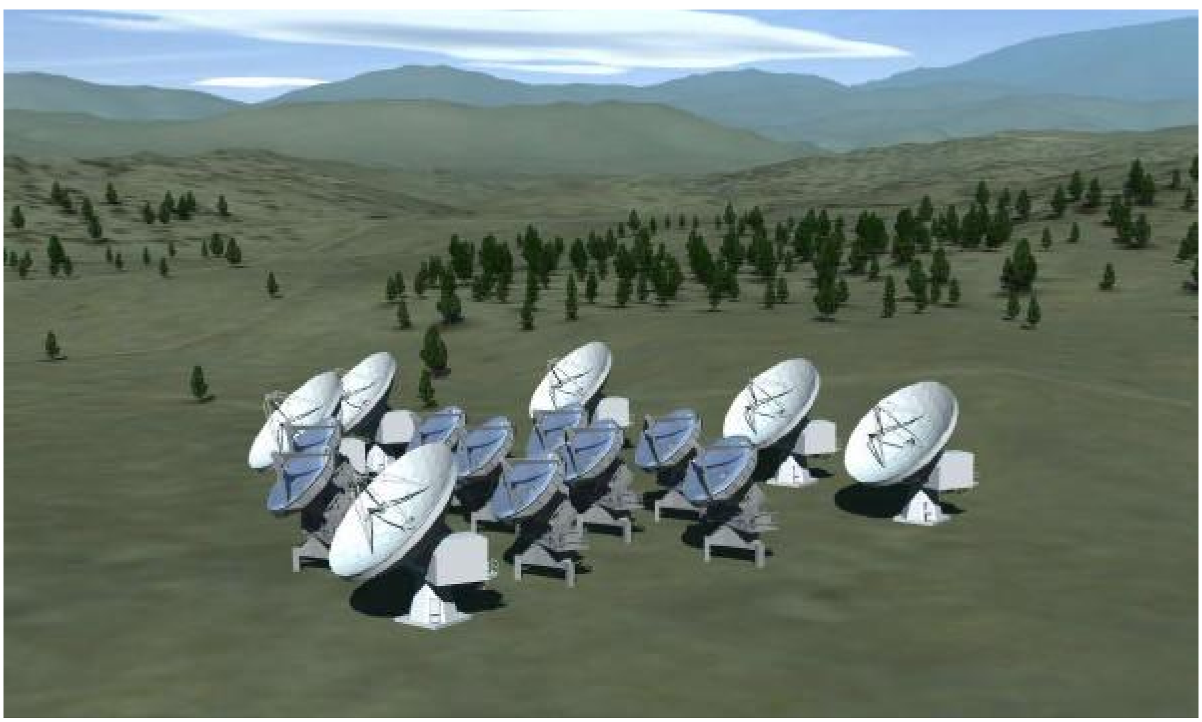
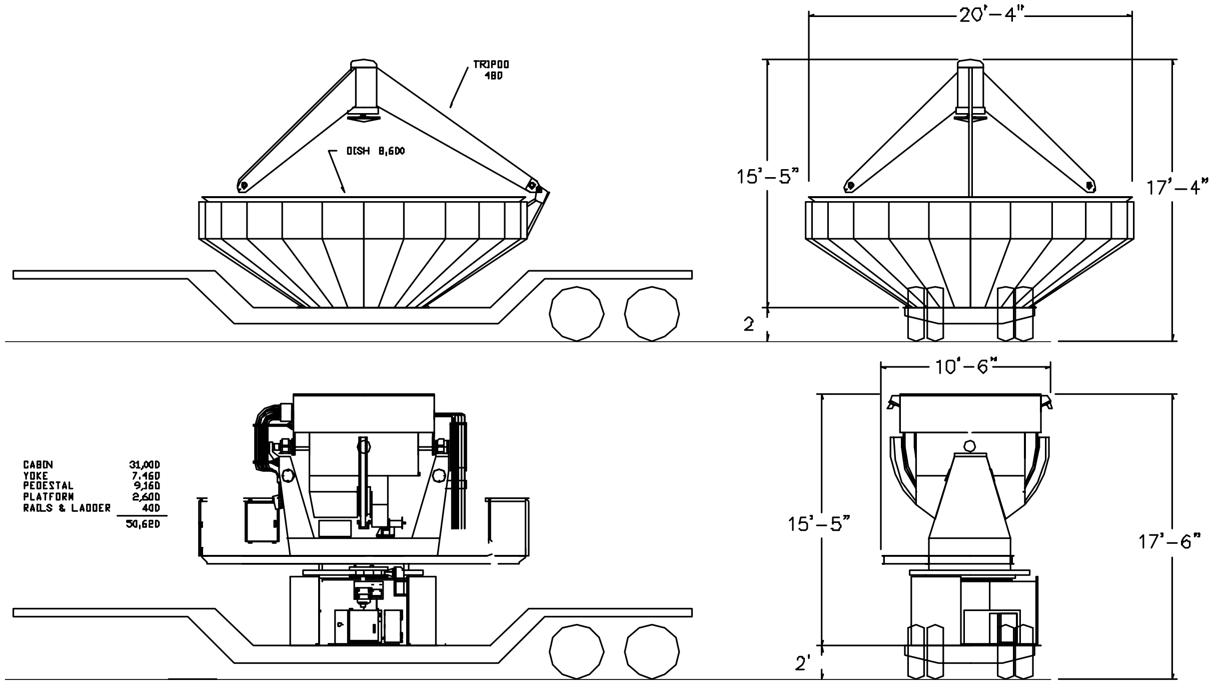


Fig. 3. Simulation of the 10.4 m and 6.1 m antennas in the most compact E-array configuration at Cedar Flat. Anti-collision trip wires on the 6.1 m antennas allow these antennas to be positioned with overlapping swept volumes and have antenna spacings as short at 7m.



Fi.e 4. A BIMA 6.1 m antenna disassembled and mounted on two low-bed trailers for transporting on state highways.

3. ANTENNAS

Telescopes are often kept productive for many decades by upgrading their detectors and instrumentation. This will be true for the BIMA and OVRO antennas with the added benefit and complexity of being transported to a new better site.

The BIMA array started operation in the early 1970's and the first 10.4 m OVRO antenna was commissioned in the late 1970's. These instruments have been very productive in the 3 mm and 1.3 mm bands for the last two decades. One of the major challenges for CARMA will to transport these antennas to Cedar Flat without degrading their pointing or surface figure. Although the antennas in both arrays are routinely moved a few hundred meters, they were not designed to be trucked 500km from Hat Creek to Cedar Flat, or even from the Owens Valley into the Inyo Mountains.

The reflector and backup structure of the BIMA antennas will be separated from their pedestal and receiver cabin and the two main pieces placed on two low-bed trailers for shipping. This is shown schematically in Fig. 4. Eighteen truck loads will be required to transport the nine BIMA antennas to Cedar Flat. The three-legged base will be discarded and replaced with a four-legged base that is compatible with the base on the OVRO antennas when the antennas are reassembled at Cedar Flat. Only one pad design is required to support both types of antennas.

Although the OVRO antennas only need to be transported 50 km to Cedar Flat, it is a tricky procedure. The 10.4 m antennas will not fit through a narrow canyon along the road without taking the reflectors off and tipping them on their sides. Fortunately, Bob Leighton designed the 10.4 m antennas with a convenient mounting plane between the reflector and the tipping structure[4]. A crane will be used to lift the reflector off the antenna mount and place it on a specially built tipping structure with an air-shock suspension system mounted on a 3 m wide low-bed trailer. The reflector will then be tipped 90 degrees, as shown in Fig. 5, before being driven up to Cedar Flat. A separate low-bed trailer will be used to truck the mount to Cedar Flat where the process will be reversed to reassemble the antenna. This will be repeated for each of the six OVRO antennas.

The eight 3.5 m antennas from the SZA are brand new. They will be trucked intact to Cedar Flat.

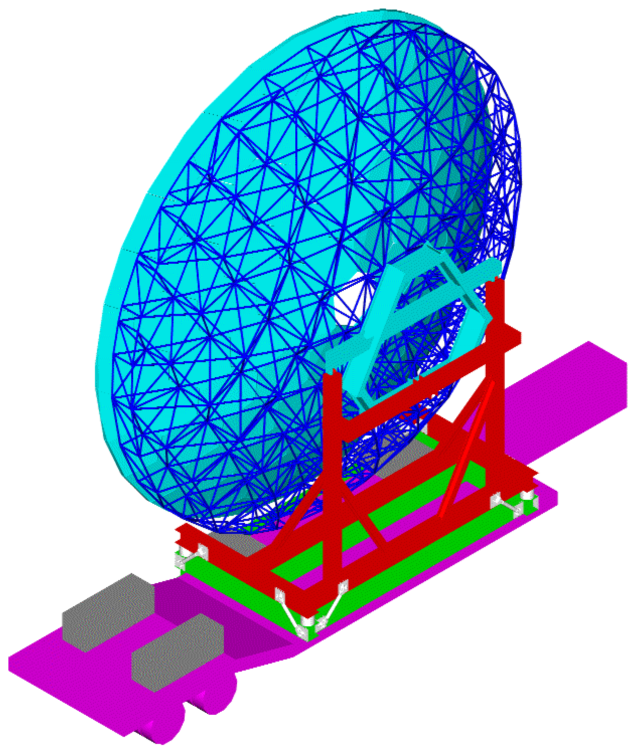


Fig. 5. Sketch of a 10.4 m reflector from one of the OVRO antennas mounted on a low-bed trailer.

Building CARMA is an opportunity to modernize and upgrade critical parts of the antennas. The mechanics of the antennas are still in excellent condition, even after more than twenty years of operation, but the wiring of the oldest OVRO antennas will be replaced. Also the OVRO antennas slew at half the speed of the BIMA antennas and the plans are to increase the size of the motors and change the gear reduction in the drives to double the slew speed to match the BIMA antennas. This will improve the mosaicing efficiency when operating as a hybrid array.

The panels will be left on the reflectors for all three sets of antennas and the reassembled antennas should be immediately usable at the longer wavelengths. Provision is being made for using holography to re-align the panels to achieve high aperture efficiency at 1.3 mm should it be necessary.

The 6.1 m and 10.4 m antennas will be moved among the configurations at Cedar Flat using a tractor and trailer. The roads on site will be dirt and gravel and it is necessary to have a rubber-tired vehicle that can transport the antennas and gently set them down to a precision of a few millimeters. The tractor is a standard six-wheel drive military vehicle while the trailer is a full custom design. A diagram of this transporter system hauling a 10.4 m antenna is shown in Fig. 6. The trailer has three lifting and three horizontal positioning hydraulic cylinders for manipulating the telescope during the lifting and set down procedure. A large forklift will be used to move the 3.5 m antennas.

The stations will be simple concrete pads that are 4m x 4m x 1m thick. A vault for the power and fiber optics cables is located in the center of each pad. The corners of the base of the antenna will have a wide foot at the end of an adjustable jack. The wide feet will spread the load on the pad giving an acceptable load pressure on the bare concrete. All of the antennas have built-in tiltmeters that are used for pointing corrections and these same tiltmeters will be used during the set down procedure to ensure that the azimuth axis is properly aligned with vertical and that the four feet share the load equally. Carefully surveyed marks in the pad and a sighting system on the telescope bases will be used to guide the set down of the antennas to the correct position and orientation. Tensioning cables connected to simple hooks in the concrete will be used to hold the antennas in place during the unlikely event of winds greater than 60 m/s or an earthquake.

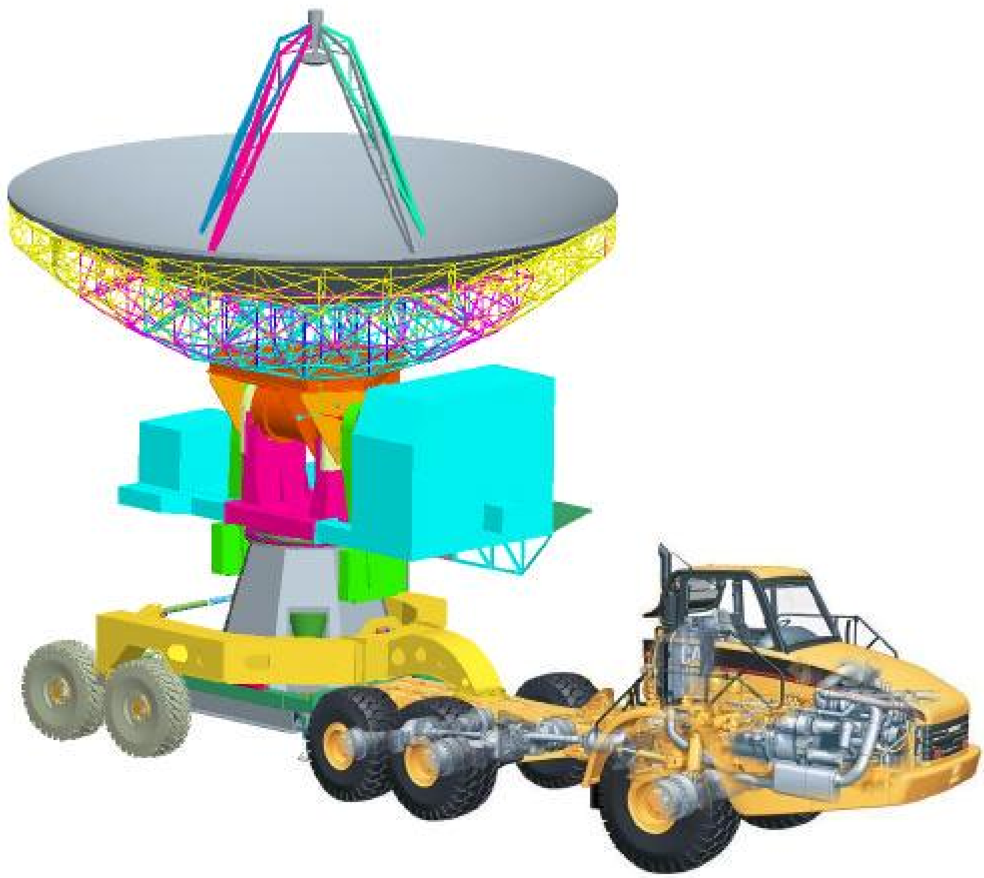


Fig. 6. Transporter with 10.4 m antenna.

4. RECEIVERS

The CARMA array will operate in three different receiver bands; 26-36 GHz (1 cm band), 86-115 GHz (3 mm band) and 205-265 GHz (1.3 mm band). The receivers developed by the CARMA member institutions and implemented on the existing arrays are close to the state-of-the-art and will initially be left unchanged to expedite the integration of the antennas into CARMA. The receivers are a major component in determining the system temperature and receiver development will continue to be very important for CARMA. All of the receivers are currently single linear polarization systems. Dual polarization receivers in all three bands will be a high priority development project.

The 1 cm band receivers use discrete InP HEMT amplifiers cooled to 15K. These are based on a design developed by Pospieszalski with chips provided by the National Radio Astronomy Observatory (NRAO)[5]. Excellent performance is obtained across the full band. The single sideband receiver noise for the eight receivers on the 3.5 m SZA antennas is between 12 and 18 K. Similar receivers will also installed on the 10.4 m antennas.

All CARMA antennas will have receivers covering the 3 mm band. MMIC amplifiers are used on the 3.5 m antennas. These amplifiers use chips and an amplifier block design from Neal Erickson at the University of Massachusetts[6]. These amplifiers are mounted next to the 1cm band receivers in the 15 K cryostat. Their single sideband noise temperature varies from typically ~45 K below 100 GHz and to ~65 K at 115 GHz. OVRO and BIMA have developed Superconductor Insulator Superconductor (SIS) heterodyne receivers for the 3 mm band. The BIMA receivers are optimized for low noise over an ~1GHz IF bandwidth while the OVRO receivers are optimized for good performance over a 4 GHz IF bandwidth. The double sideband noise temperatures are 30 to 50 K[7]. There is an active effort to obtain the best noise temperature across the full 3mm band in a 1-5 GHz IF band.

Initially only the 6.1 m and 10.4 m antennas will have receivers for the 1.3 mm band. Space has been allocated for installing 1.3 mm band receivers on the 3.5 m antennas later in the project. The receivers are double sideband SIS heterodyne mixers. The OVRO mixers have HEMT IF amplifiers integrated into the mixer blocks and produce double sideband noise temperatures of 40-60 K over the 4 GHz IF bandwidth[8]. The BIMA SIS heterodyne receivers will be upgraded to match the same 4 GHz IF band.

The LO system is a challenging part of any interferometer system, that is especially true for millimeter interferometers where 1deg of phase corresponds to only 10^{-14} sec of delay. The LO is based upon the XL Microwave™ phase lock circuits with the reference signal sent out over single-mode fiber optic cables. A line length measuring system using round trip optical signals on two fibers has been developed at Berkeley and will be used for CARMA. Care was taken to build an LO system that allowed the 85-115 GHz SZA, BIMA and OVRO receivers to lock to the same LO reference and yet keep the MMIC system single sideband while using the same 1-9 GHz IF fiber optic transmission system.

5. CORRELATOR

The CARMA correlator is being built to process 8 GHz of bandwidth from the sky. This will be accomplished with the double sideband SIS heterodyne receivers by processing the 1-5 GHz IF band and sideband separation after correlation. The single sideband HEMT and MMIC amplifier receivers produce 8 GHz of bandwidth directly. The wideband width not only increases the sensitivity for continuum observations but also helps in the search for lines and allows the observation of several lines simultaneously.

The correlator for CARMA is an extension of the COBRA correlator currently in use at OVRO. The IF band is downconverted to produce multiple base bands of 0.5-1.0 GHz to feed the 2-bit digitizer followed by an FPGA based cross-correlator. At full bandwidth the spectral resolution is 16 channels across each 500MHz wide base band. Higher spectral resolution is obtained by a combination of analog filters and FIR filtering of the digital data stream in the digitizer cards. The resolution is selectable in factors of two down 128 channels across a 2 MHz band. This correlator is described in more detail in a companion paper in these proceedings[9].

There will be two first-light correlators; one with eight downconverter, digitizer and correlator module sets to process 4 GHz of IF bandwidth from 15 antennas and another with 16 module sets to process 8 GHz of IF bandwidth from eight antennas.

6. COMPUTING

Software and computing is becoming increasingly important in modern instruments and CARMA is no exception. One of the challenges for CARMA was to integrate the three different types of telescopes and hardware into a modern software and computing system to control and monitor the antennas in several independent reconfigurable subarrays. An in depth review of the CARMA computing effort is given by Scott, et.al[10].

Essentially the whole computer system is being replaced with a distributed system of Intel/LINUX boxes and embedded microprocessors. One of the more challenging aspects of doing this is coordinating the software development among the software engineers at all five institutions. Low level microprocessor code is in C while the higher levels of the system is programmed primarily in C++, with computer to computer communications and data transfer via a Common Object Request Broker Architecture (CORBA). All of the code is developed using a common Concurrent Versioning System (CVS) repository for the project with quasi-continuous automatic build and test suite system using Tinderbox.

All of the new hardware being developed for CARMA uses the same XAC3 Phycore™ microprocessor module and a Computer Area Network bus (CANbus) is used for communication. The module provides a microprocessor with EEPROM, CANbus driver chips and other “glue” chips. A CANbus protocol has been developed that matches the CARMA requirements and provides a deterministic and easy to use hardware control and monitor system. The 19-bit message header that is part of the CANbus definition is divided into fields that encode the hardware location and function as well as the control or data message type. There are two modes that allow addressing the hardware by its function and location or by a particular hardware board type and serial number with defaults for commanding all modules with the same function using a single command message. Although most of the anticipated communication will be between the modules and a “master” LINUX box, peer-to-peer and broadcast messaging is also supported. The address field lengths limit the number of different types and quantities of devices that can be accommodated, but these are well within the anticipated CARMA requirements.

One of the major advantages of using a field bus like CANbus is that it allows separation of the hardware engineering tasks which are typically performed on a Microsoft Windows™ platform from the higher level control and monitor system implemented in the distributed LINUX system. In addition, all of the operations requiring precise and/or fast timing are performed in the microprocessor and a real time operating system is not required in the LINUX boxes.

It can be very costly and complicated to maintain many different types of processors and operating systems. To this end CARMA uses the same compact-PCI crate and processor running the same LINUX release throughout the array. Thus a single set of spares and basic PXE boot files suffice for the whole array. The exception to this is the Central Array Computer (ACC) and data pipeline processor, which are multi-processor workstations.

The monitor system provides a flow of information up from the embedded microprocessors to the central ACC that is based on half-second frames, synchronized to absolute time. This flow provides a heartbeat as well as the continuous status of approximately 27,000 monitor points. Monitor points may be sampled at rates as high as 100 Hz, but 2 Hz is the typical rate. The monitor data is archived in a short-term database, while averages, maximums and minimums for time scales of one minute and the astronomical integrations reside in the permanent archive. The correlation data is also produced in half-second frames and then integrated up to form the astronomical data.

7. ARRAY CAPABILITIES

The combination of moving to a higher site, adding antennas of three different diameters plus the large correlator bandwidth makes CARMA a very powerful imaging instrument. It will have a total collecting area of 770 m^2 and measure the visibilities on baselines ranging from 3.5 m to 1.9 km, providing a spatial dynamic range greater than 500. The estimated array sensitivities are given in table 1.

Table 1: CARMA First-light Sensitivity

CONTINUUM SENSITIVITY 4 GHZ BW 1-POLARIZATION			ANGULAR RESOLUTION & LINE SENSITIVITY (1 KM/S CHANNEL, 1-POLARIZATION)	100 GHZ			230 GHZ		
Freq GHz	1-min mJy	4-hr mJy	Config	Beam “	1-min K	4-hr K	Beam “	1-min K	4-hr K
100	1.3	0.09	E	11.5	0.14	0.009	5.0	0.3	0.02
230	4.4	0.28	D	5.5	0.59	0.038	2.4	1.3	0.08
			C	2.2	3.8	0.25	.94	8.3	0.54
			B	.85	25	1.6	0.37	54	3.5
			A	0.35	150	9.7	0.15	326	21

Assumptions: 6 x 10.4 m antennas + 9 x 6.1 m antennas (i.e. no SZA), T_{SYS} ~80 K at 3 mm, 140 K at 1 mm; 70 % antenna efficiency. Resolution indicated is λ/D_{max}, i.e. no tapering and uniform weighting.

Many interesting astronomical objects have extended structure and correct interpretation requires high fidelity images of the extended structure. Interferometer arrays consisting of a single antenna size suffer from a hole in the visibility data at center of the UV-plane with a diameter of about the same size as the dish diameter. Single dish data fills in the very center of the UV-plane. Mosaic observations can help fill in this UV hole, but a more direct approach is to use smaller antennas in a compact array to measure the visibilities on the short spacings. The CARMA array with its 3.5, 6.1 and 10.4 m antennas is ideally used to this task.

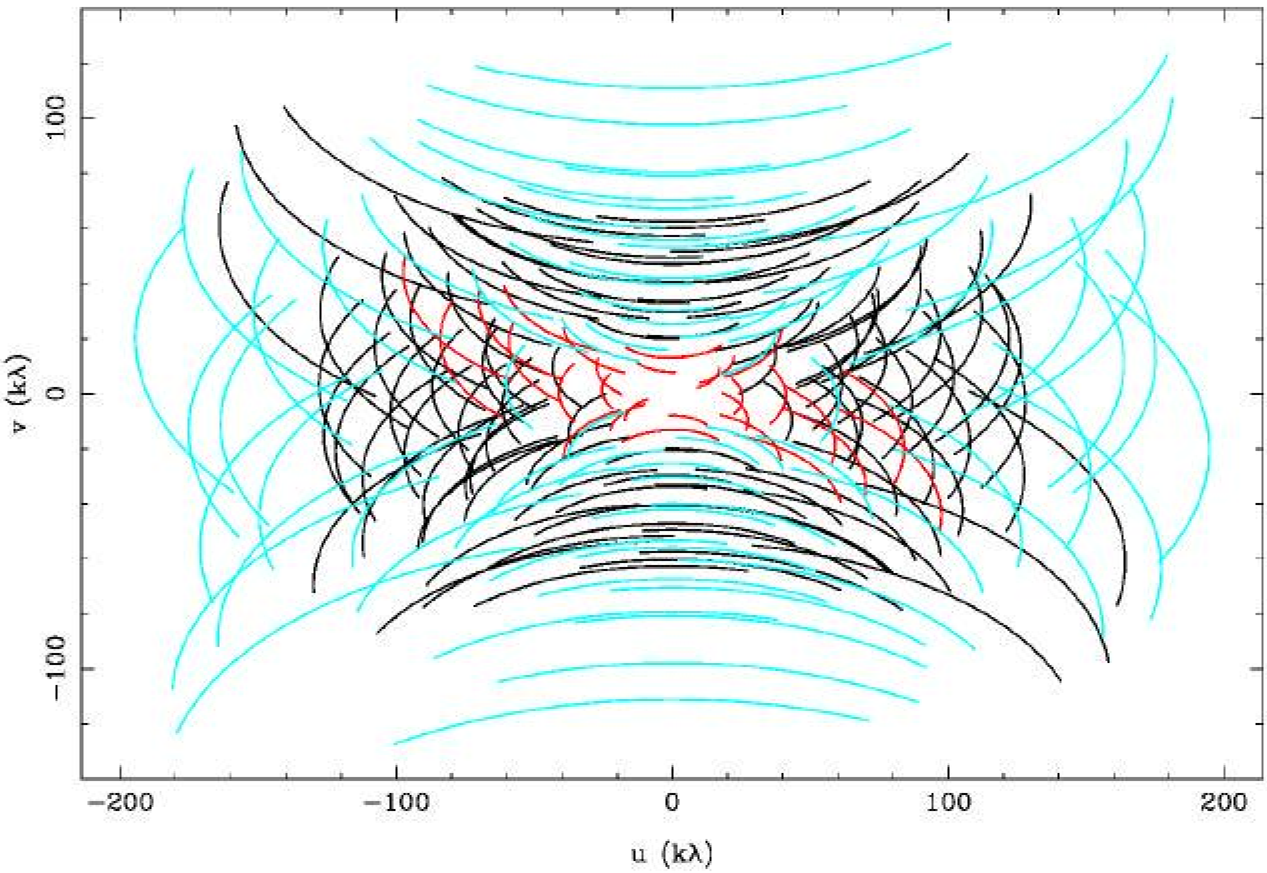


Fig. 7. UV coverage for 15 antennas in the C-configuration at a wavelength of 1.3 mm. The source is at –30 deg dec and is tracked from –2 to +2 hrs. The colors (gray-scale) encode the various combinations of antenna diameters; the longer baselines are 10.4 m antennas pairs, while the shortest baselines are 6.1 m antenna pairs. The black (dark) tracks are the hybrid pairings of 10.4 m antennas with 6.1 m.

Single dish data from the 10.4 m antennas are an excellent compliment to the visibilities measured by the 3.5 and 6.1 m antennas in their most compact configurations. The optics on the 10.4 m antennas have been designed to support a nutator at an image of the primary. This will be implemented as part of a future CARMA enhancement. This will allow CARMA to make high fidelity images of even the most extended galaxies, clusters and clouds within our galaxy.

The five array configurations each provide complete azimuth uv-coverage in a 4 hour observation at all declinations >-30 degrees. This allows us to make observations around transit with lower opacity and better system temperatures. The 15-antenna configurations have synthesized beams with RMS sidelobes ~ 2% and peak sidelobes ~ 7% allowing high fidelity imaging. An example of the excellent UV coverage is shown in Fig. 7.

The CARMA antennas can be configured into several independent subarrays. The hardware and software interfaces to all 23 antennas are identical and a fiber optics patch panel in the control building is used to assign the antennas to one of three subarrays. There are three LO tone generators and control software to support these subarrays.

One of the major limitations to millimeter interferometry is the variable phase delay caused by water vapor in the atmosphere. The turbulence in the atmosphere introduces temporal and spatial variability in the amount of water vapor along the line of sight of each telescope in the array. Fortunately the amount of water vapor along the optical path can be detected by its line emission. OVRO has radiometers sensitive to the 22 GHz water vapor emission line deployed on its millimeter array telescopes and BIMA is developing a system for its telescopes. The OVRO system has demonstrated that the quality of the astronomical images can be improved dramatically using the data from the

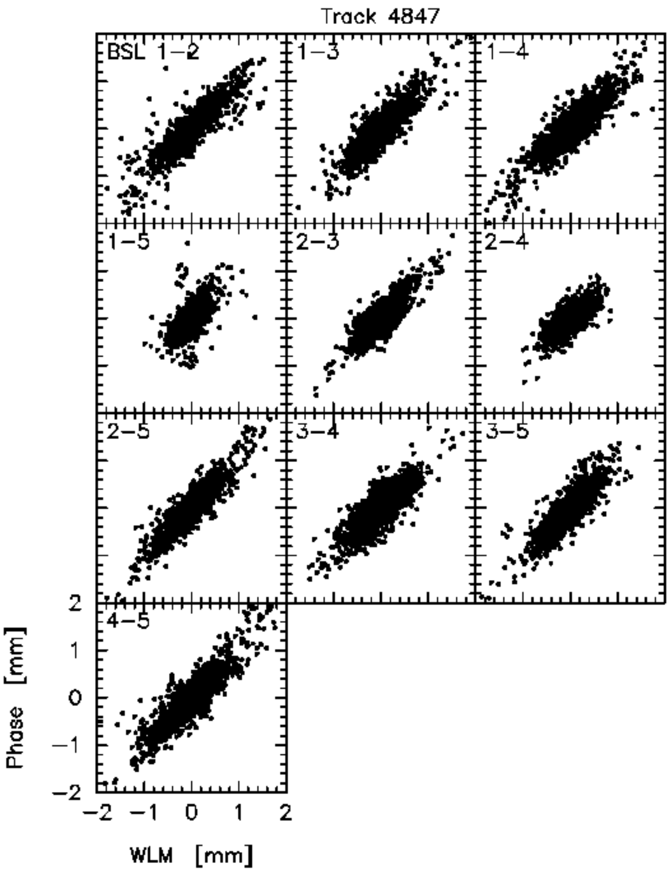


Fig. 8. Correlation of the astronomically measured phases for a Quasar with the delay deduced from the OVRO 22 GHz water vapor radiometers on the 10 baselines from five antennas. The antenna pairs are labeled in the upper left corner of each panel. The observations spanned five hours. and the longest baselines are ~200 m for antenna pair 1-4 while the shortest baselines are for antenna pair 2-4.

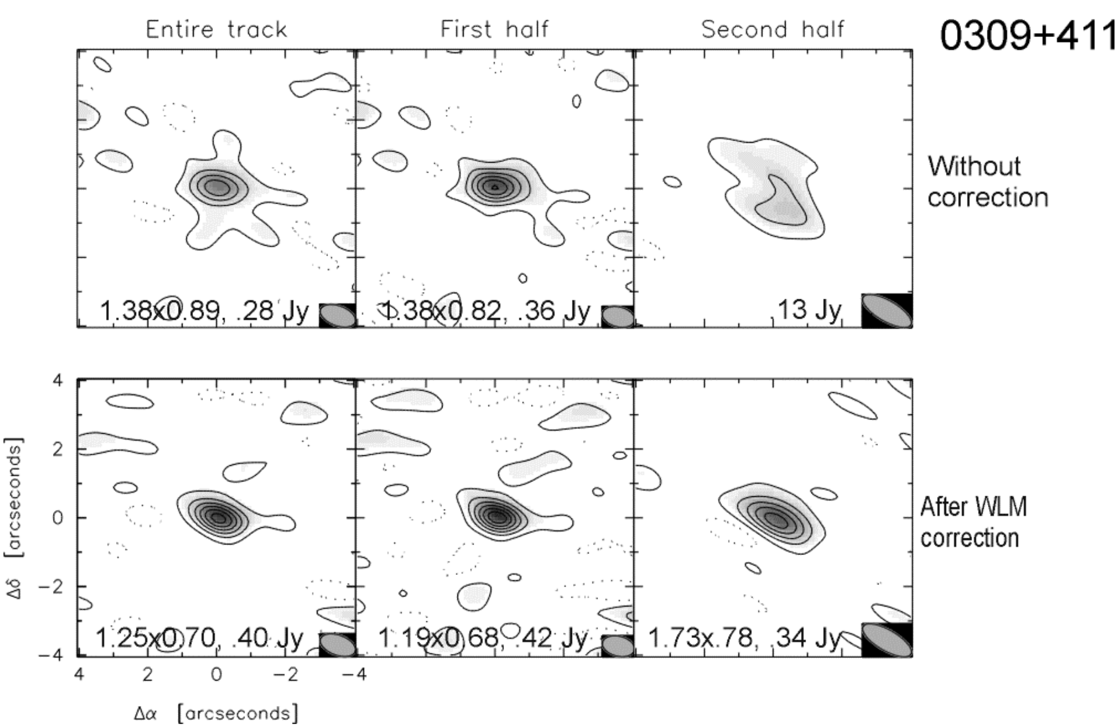


Fig. 9. An example of the improvement that is possible with 22 GHz water vapor delay correction.

radiometers to correct for the fluctuations in the atmospheric water vapor[11]. Figure 8 shows the correlations between the astronomically measured phases on ten baselines and the delay deduced from the 22 GHz radiometers. The longer baselines show larger delay fluctuations as expected for a Kolmogorov spatial structure function. The correlation coefficients are high with an uncorrelated or noise component corresponding an RMS delay error of ~0.2 mm. This is a typical result, but significantly worse as well as better correlations are often observed. Figure 9 shows the before and after images of one of the more successful applications of the radiometer data for image correction. Improving the 22 GHz water vapor radiometer technique and producing water vapor delay corrected visibilities in the processing pipeline is a important goal for the CARMA project.

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